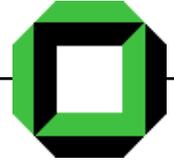


VBFNLO

NLO Parton Level Monte Carlo for VBF

*Dieter Zeppenfeld
Universität Karlsruhe (ITP)
La Thuile 23 June 2007*

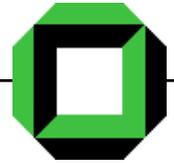
<http://www-itp.physik.uni-karlsruhe.de/~vbfnlweb/>



- *What is VBFNLO*
- *Why we need VBFNLO - signal versus background*
- *Features of VBF processes*
- *Features of VBFNLO parton level MC program*
- *How to use VBFNLO*
- *Results $qq \rightarrow qqH, qq \rightarrow qqW^+W^-$*
- *Summary & Outlook*

Manuel Bähr, *Giuseppe Bozzi*, Christoph Englert, Terrance Figy, Co Georg, Jan Germer, Nicolas Greiner, *Vera Hankele*, *Barbara Jäger*,
Gunnar Klämke, Partha Konar, Michael Kubocz, *Carlo Oleari*, Matthias Werner, *Malgorzata Worek*, DZ

Special thanks to Malgorzata Worek



- *Parton level Monte Carlo for various VBF processes at NLO QCD*
- *Arbitrary cuts can be implemented*
- *Various scale choices and PDF sets*
- *Cross sections at LO and NLO QCD*
- *Arbitrary differential distributions at LO and NLO*
- *Anomalous HVV couplings both in the production and decay of the Higgs boson*
- *Anomalous triple gauge couplings in WWjj*
- *K-Factors and differential K-Factors*
- *Weighted/unweighted events and LHA format files for LO processes*

NLO QCD:

$$pp \rightarrow Hjj$$

$$pp \rightarrow Hjj, \quad H \rightarrow \tau\tau$$

$$pp \rightarrow Hjj, \quad H \rightarrow \gamma\gamma$$

$$pp \rightarrow Hjj, \quad H \rightarrow b\bar{b}$$

$$pp \rightarrow Hjj, \quad H \rightarrow WW \rightarrow l^+l^-\nu\bar{\nu}$$

$$pp \rightarrow WWjj \rightarrow l^+l^-\nu\bar{\nu}jj$$

$$pp \rightarrow ZZjj \rightarrow l^+l^-l^+l^-jj$$

$$pp \rightarrow ZZjj \rightarrow l^+l^-\nu\bar{\nu}jj$$

$$pp \rightarrow Wjj \rightarrow l\nu jj$$

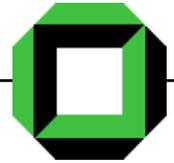
$$pp \rightarrow Zjj \rightarrow l^+l^-jj$$

$$pp \rightarrow Zjj \rightarrow \nu\bar{\nu}jj$$

LO:

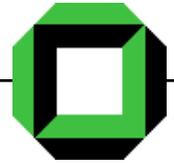
All processes plus additional jet

Higgs Production in VBF



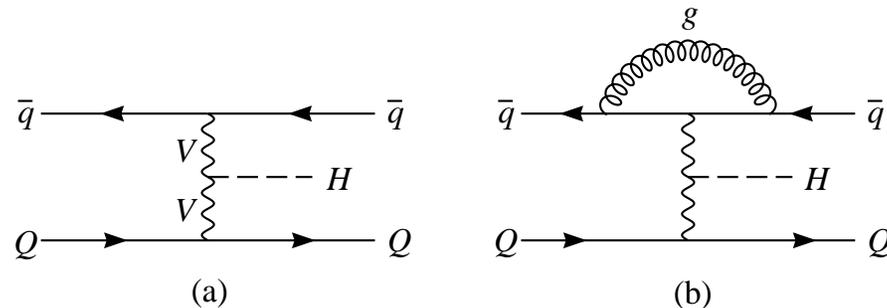
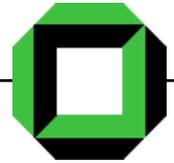
- $\sigma(qq \rightarrow qqH) \sim 20\% \sigma(gg \rightarrow H)$ at the LHC
- Clean experimental signature
 - Energetic jets in forward and backward directions $p_T > 20 \text{ GeV}$
 - Large rapidity separation and large invariant mass of two tagging jets
 - Higgs decay products between tagging jets
 - Little gluon radiation in the central rapidity region due to colourless W/Z exchange
- Double jet tagging and central jet veto to suppress QCD backgrounds
- Allows precise measurement of Higgs couplings $\Rightarrow HWW, HZZ, Hf\bar{f}$
- At the LHC with statistical accuracies on $\sigma \times BR$ of order 10%

D. Zeppenfeld, R. Kinnunen, A. Nikitenko, E. Richter-Was, *Phys. Rev. D* 62, 013009 (2000) **Les Houches 1999**



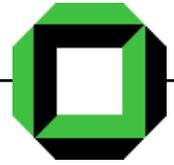
- *Background to Higgs production via VBF*
 - $\sigma(qq \rightarrow qqW^+W^-)$ between 15% and 3.5% of the Higgs signal for $115 \text{ GeV} \leq M_H \leq 160 \text{ GeV}$
- *Similar features as H production \Rightarrow Irreducible background*
 - *t-channel colour-singlet exchange VBF process*
 - *Kinematic distributions of the two tagging jets*
 - *Suppression of gluon radiation in the central region*
- *Want to check unitarity restoration in elastic WW scattering at high m_{WW} :*
 - *SM $qq \rightarrow qqW^+W^-$ cross sections must be known precisely*
 - \Rightarrow *NLO QCD corrections*

Practical Simplifications: H Production

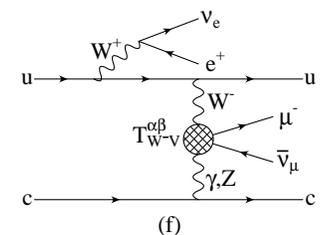
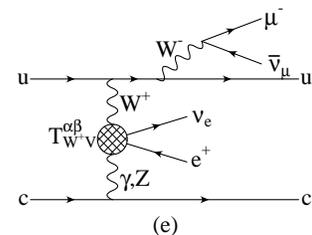
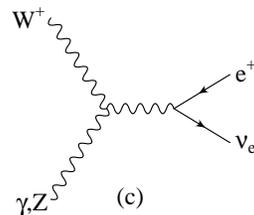
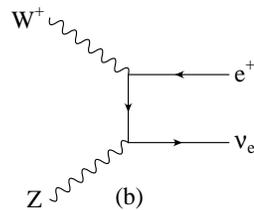
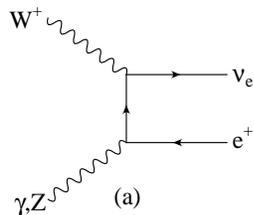
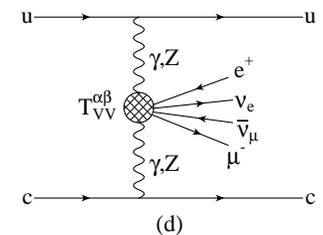
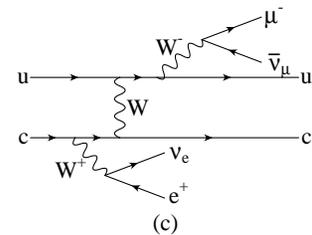
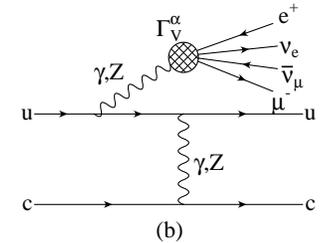
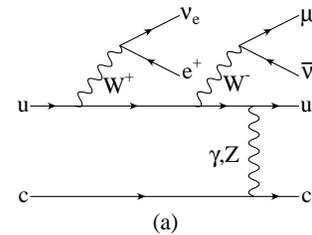
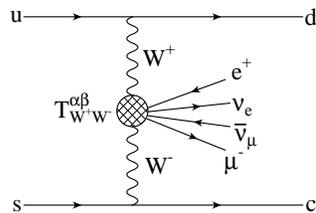


- Single Feynman Diagram for different quark flavors on the two fermion lines
- Any identical fermion effects systematically neglected \Rightarrow 0.3% at LO
- $\bar{q}q \rightarrow Z^* \rightarrow ZH; Z \rightarrow \bar{q}q$
- Interchange of identical quarks in the initial or final state $qq \rightarrow qqH, \bar{q}\bar{q} \rightarrow \bar{q}\bar{q}H$
- Strongly suppressed by large momentum transfer in the weak boson propagator in the phase space regions where VBF can be observed experimentally
- Colour singlet structure of exchanged weak boson \Rightarrow no interference between gluons attached to both upper and lower quark lines
- Use these approximations/features also for the more complex VBF processes

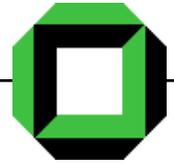
WW production in VBF



- WW production via VBF with leptonic decays $pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu + 2j$
- Spin correlations of the final state leptons
- All resonant and non-resonant Feynman diagrams included
- NC \Rightarrow 181 Feynman diagrams
- CC \Rightarrow 92 Feynman diagrams



Tools for the Calculation



- *Amplitudes are calculated using helicity amplitudes \Rightarrow checked with MADGRAPH*
- *MC integration \Rightarrow modified version of VEGAS*
- *Optimised phase space for up to 7 particles in the final state*
- *PDF via LHAPDF or build-in CTEQ6m, CTEQ6L1*
- *No mandatory external libraries*
- *Parallelised through the separation of random numbers seeds \Rightarrow Condor Cluster*
- *Passarino-Veltman reduction of tensor integrals up to box-type virtual corrections*

G. Passarino, M. J. Veltman, Nucl. Phys. B160, 151 (1979)

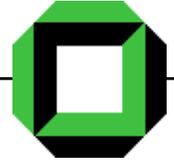
- *Reduction scheme proposed by Denner and Dittmaier for pentagon-type*

A. Denner, S. Dittmaier, Nucl. Phys. B658, 175 (2003), B734, 62 (2006)

- *Dipole subtraction formalism in the version proposed by Catani and Seymour*

S. Catani, M. H. Seymour, Nucl. Phys. B485, 291 (1997)

Performance



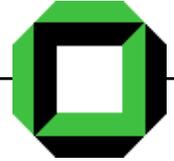
<i>Process</i>	<i>Events</i>	<i>Time</i>	<i>Unweighting eff.</i>
$pp \rightarrow Hjj$	16017	11s	6 %
$pp \rightarrow H(\rightarrow WW)jj$	12401	54s	0.6 %
$pp \rightarrow Hjjj$	12055	2m 7s	0.6 %
$pp \rightarrow Wjj$	19852	9m 11s	0.11 %
$pp \rightarrow WWjj$	10692	5h 10m	0.03 %

● LO event files AMD Athlon 64 2.2 GHz

<i>Process</i>	<i>Error</i>	<i>Time</i>
$pp \rightarrow H(\rightarrow WW)jj$	0.7 %	2m 6s
$pp \rightarrow Wjj$	0.7 %	9m 4s
$pp \rightarrow WWjj$	1.1 %	42m

● NLO cross sections Intel Centrino 1.8 GHz

Input & Output



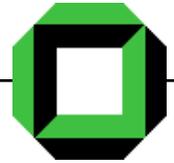
● *Input files*

- vbfno.dat** \Rightarrow *Modify the main options: process ID, beam energy, beam particles, scale choice, pdfset, output format etc*
- cuts.dat** \Rightarrow *Specify the values of the implemented cuts*
- anom-WW.dat** \Rightarrow *Set anomalous triple gauge couplings for the bosons*
- anom-HVV.dat** \Rightarrow *Set anomalous Higgs couplings*
- random.dat** \Rightarrow *Set the seeds of the random number generator*

● *Output files*

- *Histograms: ROOT, Gnuplot, Paw, Topdrawer*
- *LHA event-files as ASCII files.*

Getting Started



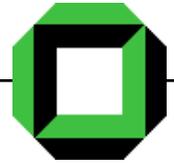
- *Download the code*
 - <http://www-itp.physik.uni-karlsruhe.de/~vbfnlweb/>
- *Extract it*
 - `$ tar -zxvf vbfnlo.tar.gz`
- *Adjust the Makefile*
 - *Choose your Fortran compiler* \Rightarrow **g77**
 - *Enter the library paths, you want to link to e.g. CERNLIB or LHAPDF*
 - *Enable the desired libraries e.g.*

WITH_LHAPDF = 1

WITH_CERNLIB = 0

WITH_ROOT = 1

Configure VBFNLO



- Adjust **vbfno.dat**
- **L^AT_EX** files are provided in **.ldoc/** to explain the options
 - *process_list.tex*, *scales.tex*, *ew_scheme.tex*
 - *Manual.tex* \Rightarrow **\$ make gv**

PROCESS = 102

Identifier for process

LO_ITERATIONS = 4

Number of iterations at LO

NLO_ITERATIONS = 4

Number of iterations at NLO

LO_POINTS = 22

Number of points for LO $\Rightarrow 2^{22} \approx 4 \cdot 10^6$

NLO_POINTS = 22

Number of points for NLO

NLO_SWITCH = true

Switch: NLO/LO calculation

ECM = 14000d0

Collider center-of-mass energy

Configure VBFNLO



ID_MUF = 12

ID for factorisation scale

ID_MUR = 12

ID for renormalisation scale

XIF = 1d0

Scale factor xi for mu_F

XIR = 1d0

Scale factor xi for mu_R

ANOM_CPL = false

Use anomalous couplings

LHA_SWITCH = true

Les Houches Accord files only for LO calculation

UNWEIGHTING_SWITCH = true

Unweighted/weighted (T/F) events for LHA

PRENEVUNW = 1000

Number of events to calculate pre-maximal weight

TAUMASS = true

Include mass of the tau lepton(s) in the LHA file

ROOT = true

Create root-file

REPLACE = true

Replace output files

ROOTFILE = histograms

Name of root-file (+ '.root')

Configure VBFNLO



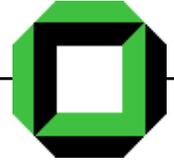
● Adjust `cuts.dat`

RJJ_MIN = 0.8d0	<i>Minimum jet-jet R separation</i>
Y_P_MAX = 5.0d0	<i>Maximum pseudorapidity for partons</i>
NJET_MIN = 2	<i>Minimum number of defined jets</i>

● Adjust VBF cuts in `cuts.dat`

ETAJJ_MIN = 4d0	<i>Minimum rapidity gap size</i>
YSIGN = true	<i>Tagging jets $y_{j_1} \cdot y_{j_2} < 0$</i>
LRAPIDGAP = true	<i>Leptons fall inside rapidity gap</i>
MDIJ_MIN = 600d0	<i>Dijet minimum mass cut on tagging jets</i>

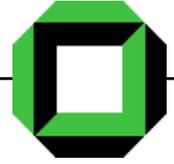
Adding new histogram



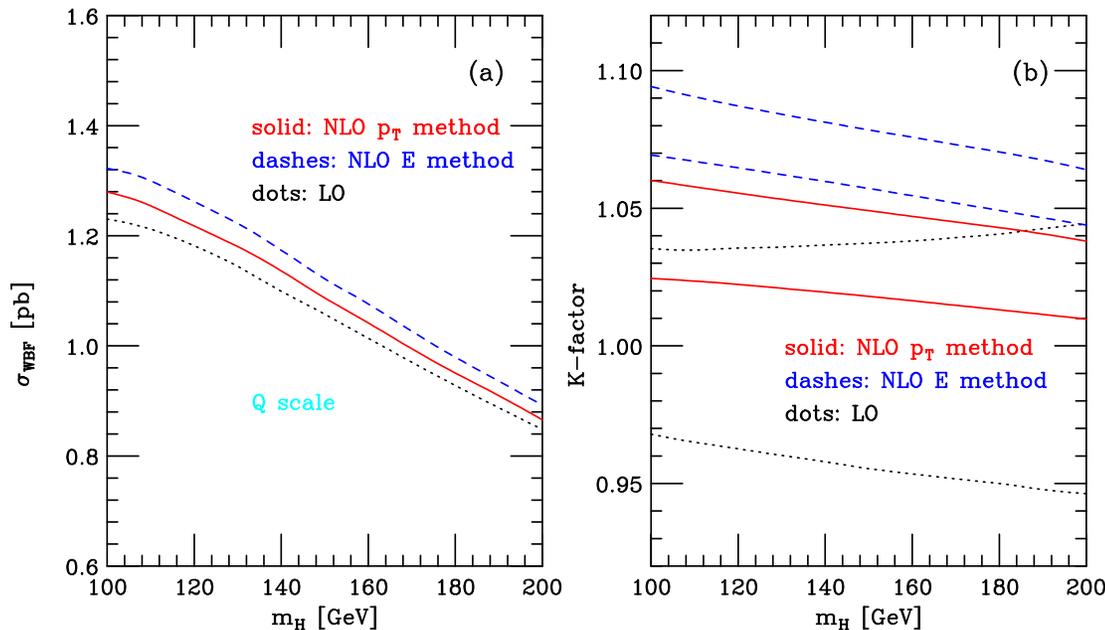
- Add new histogram in `./src/histograms.F`
 - call `CreateHist(ID, title, bins, min, max)`
 - `real*8 jets(0:7,max_jets), leptons(0:7,max_v), photons(0:7,max_v)`
 - call `FillHist(ID, value, dw, NLO)`
- As a result you will get histogram for LO and NLO

- *Recompile* \Rightarrow `$ make`
- *Run the code* \Rightarrow `$ make run`
- *Questions, comments, suggestions or bug reports, please e-mail us*
 - vbfnlo@particle.uni-karlsruhe.de

$qq \rightarrow qqH$



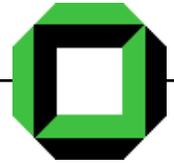
- Higgs boson production cross section via VBF as a function of m_H
- Total cross section within the cuts
- Scale dependence for variation of μ_R and μ_F by a factor of 2
- NLO effects modest 3%-5% for p_T method, 6%-9% for E_T method



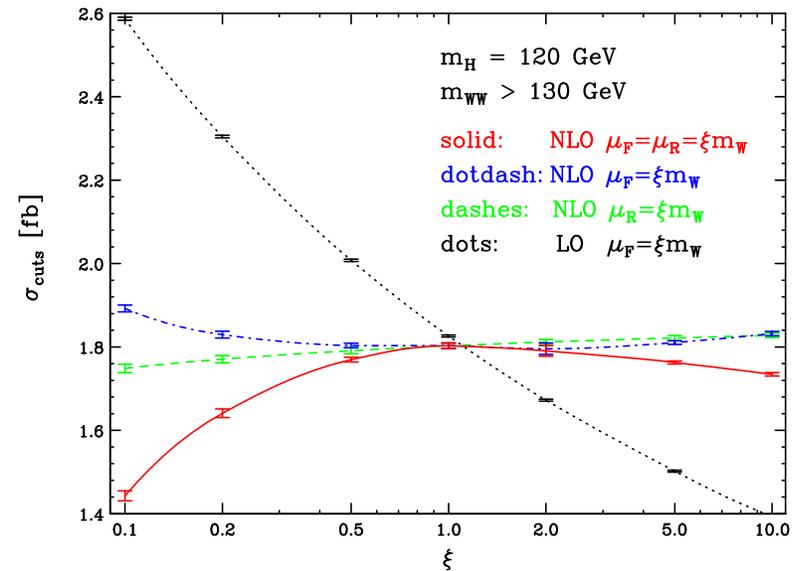
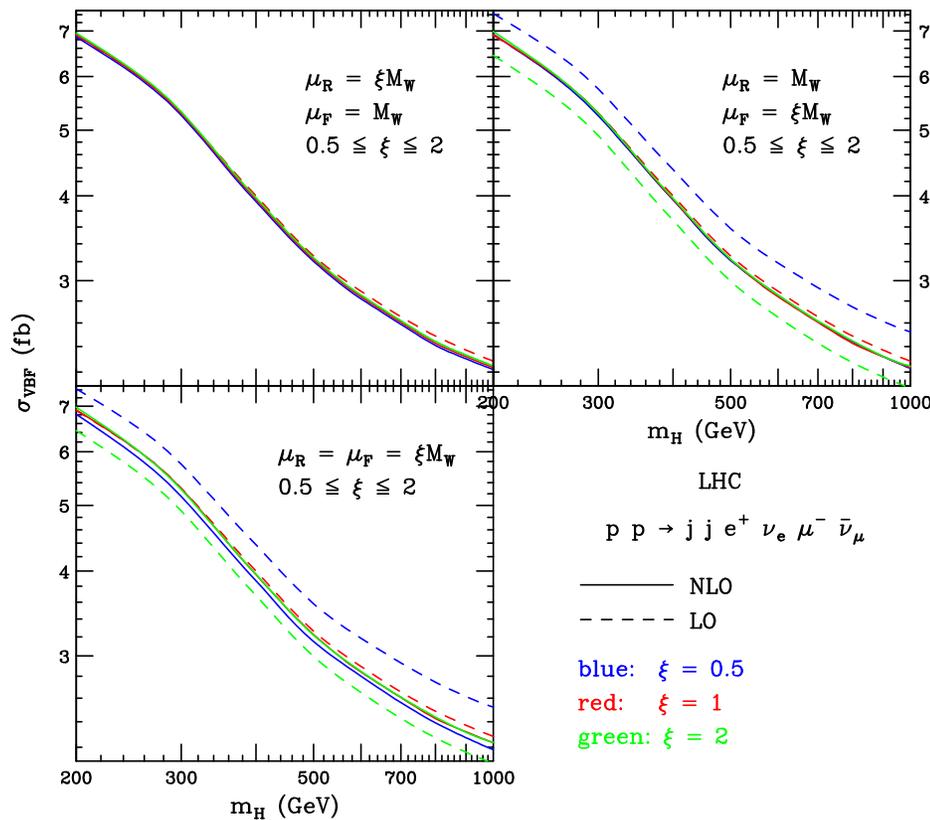
- k_T algorithm
- $y_{j_1} < \eta_{1,2} < y_{j_2}$
- $y_{j_1} \cdot y_{j_2} < 0$
- $\Delta y_{j_1 j_2} = |y_{j_1} - y_{j_2}| > 4$
- NLO \Rightarrow CTEQ6M
- LO \Rightarrow CTEQ6L1
- $K = \frac{\sigma^{NLO}(\mu_R, \mu_F)}{\sigma^{LO}(\mu_F = Q_i)}$

T. Figy, D. Zeppenfeld, C. Oleari, Phys. Rev. D68, 073005 (2003)

$qq \rightarrow qqWW$

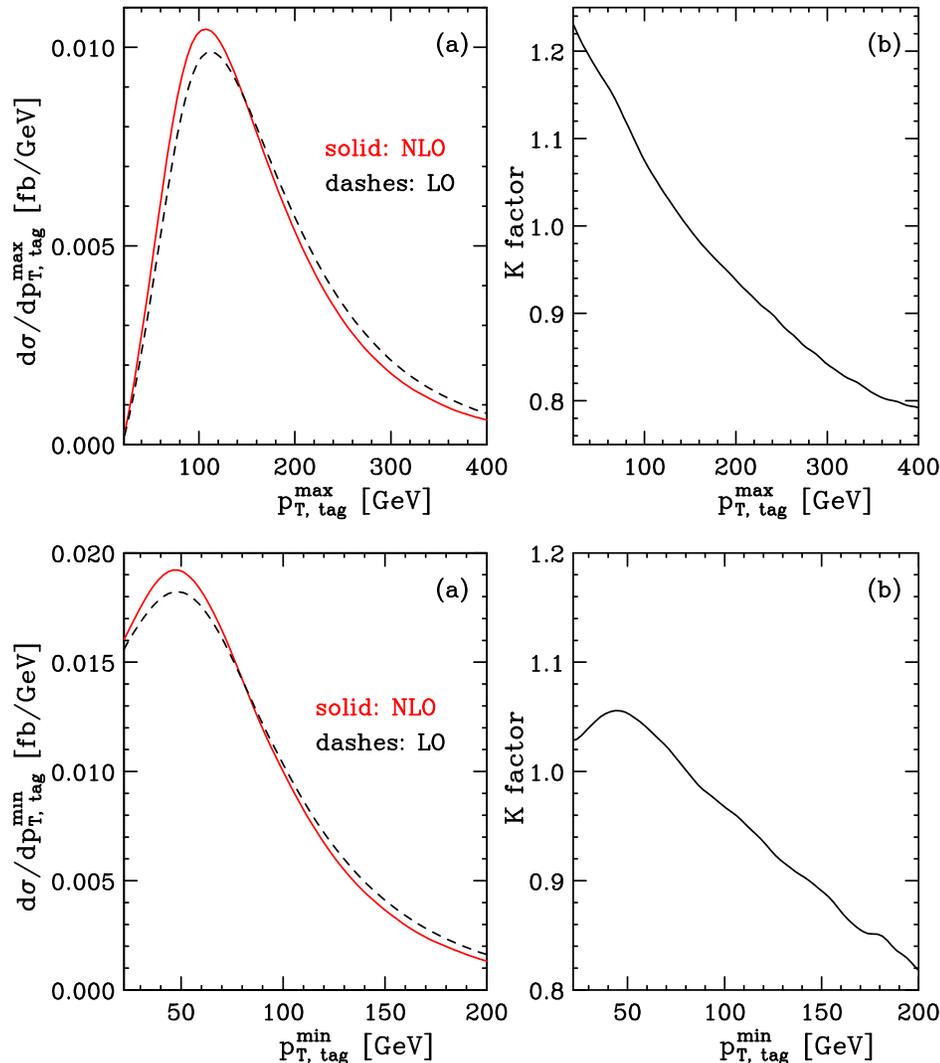
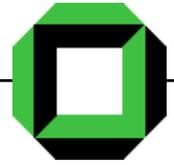


- Scale dependence of the total cross section without Higgs contribution
- Higgs mass dependence of the total cross section
- NLO cross section quite insensitive to scale variation \Rightarrow changes less than 2%



B. Jäger, C. Oleari, D. Zeppenfeld, JHEP 07, 015 (2006)

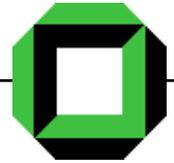
$qq \rightarrow qqWW$



B. Jäger, C. Oleari, D. Zeppenfeld, JHEP 07, 015 (2006)

- Transverse momentum distribution highest and smallest p_T tagging jet
- $m_H = 120 \text{ GeV}$
- $\mu_F = \mu_R = m_W$
- Dynamic K factor $K = \frac{d\sigma_{NLO}/dx}{d\sigma_{LO}/dx}$
- Scale variations between $0.5 \cdot m_W$ and $2 \cdot m_W$ change distributions by 2% up to 6% in the tails
- $p_{T,tag}^{max} \Rightarrow K=1.2-0.8$
- $p_{T,tag}^{min} \Rightarrow K=1.1-0.8$

Summary & Outlook



- *VBF offers promising prospect for investigation of Higgs properties*
- *VBFNLO - fully flexible parton level MC program*
- *Computation of various observables at LO and NLO QCD*
- *NLO corrections moderate and under theoretical control*
- *Future processes in VBFNLO*
 - *$pp \rightarrow WZjj \rightarrow l^+l^-l\nu jj$*
 - *$pp \rightarrow WWjj \rightarrow l\nu jjjj \Rightarrow$ hadronic W decay*
 - *$pp \rightarrow V'jj \Rightarrow$ Kaluza Klein excitations from extra dimensions, or techni-rho*
 - *$pp \rightarrow hjj, Hj j, Aj j \Rightarrow$ via gluon fusion at LO, includes finite m_t, m_b effects*

<http://www-itp.physik.uni-karlsruhe.de/~vbfweb/>